

DISINTEGRATION BY SLOW NEUTRONS

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1. It has been shown by Fermi and his collaborators* that neutrons slowed down by collisions in substances containing hydrogen are captured by many nuclei, for example, by silver, rhodium, etc., much more frequently than are fast neutrons. In all the cases at first reported, the process is one of simple capture of the neutron, with the formation of a higher isotope of the nucleus, and the emission of the excess energy as a γ -ray quantum.

One might expect that slow neutrons could also cause a nuclear transformation with the emission of heavy particles provided that energy can be released in the process. The probability of such a transformation will depend on the mutual kinetic energy and potential barrier of the resulting particles, and may be large when these quantities are of the same order of magnitude; this can in general only be expected for elements of low atomic number. As a rule, disintegration by neutrons will be "endothermic" (absorption of kinetic energy) if a proton is one of the products of transformation†, and may be "exothermic" (release of kinetic energy) if one at least of the products is an α -particle.

We have examined for such transformations all the light elements up to aluminium and some heavier ones. Evidence of disintegration by slow neutrons was found only with lithium, boron, and nitrogen‡. Amaldi and others§ have independently observed the emission of charged particles from lithium and boron bombarded by slow neutrons, and have investigated the boron reaction.

2. The general procedure of investigation was as follows. The element under examination was enclosed, as a target or where convenient as gas, in an ionization chamber connected to a linear amplifier and oscillograph. The chamber used for targets was of about 7 cm. diameter and 8 mm. depth. The element to be examined was deposited as foil or powder on the inner face of the ionization chamber. The area covered by the element was about 25 sq. cm. The chamber was filled with argon in order to reduce the effect of the recoil particles produced by the fast

* Fermi, Amaldi, Pontecorvo, Rasetti and Segrè, *Ricerca Scientifica*, 5 (1934), 2, 282.

† A possible exception is the reaction $\text{He}^3 + n^1 \rightarrow \text{H}^3 + \text{H}^1$, which according to the present values of the masses of these nuclei should be exothermic.

‡ Chadwick and Goldhaber, *Nature*, 135 (1935), 65.

§ Amaldi, d'Agostino, Fermi, Pontecorvo, Rasetti and Segrè, *Proc. Roy. Soc. A*, 149 (1935), 542.

Plate: Oscillograph records of the lithium and boron disintegration by slow neutrons.

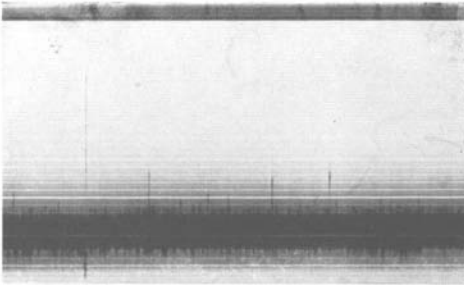


Fig. 1*a*.

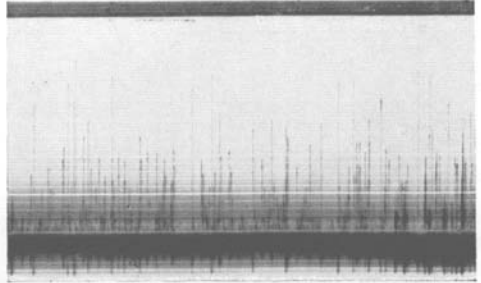


Fig. 1*b*.

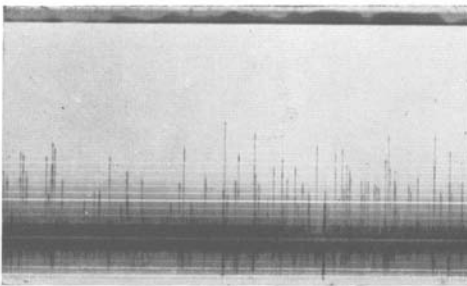


Fig. 1*c*.

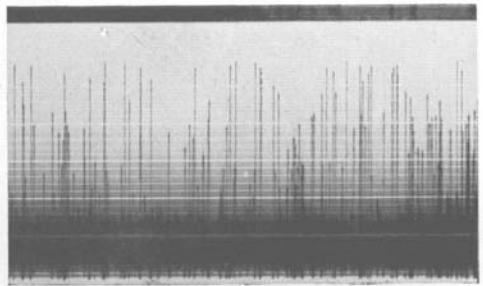


Fig. 2.

Each piece of film reproduced corresponds to a time of 45 sec.

Fig. 1. *a*. Ionization chamber containing a lithium target (about 25 cm.²) bombarded by neutrons of a radon-beryllium source (5 millicuries). 3 cm. lead between source and chamber, to reduce the γ -ray background. *b*. Source and chamber surrounded by paraffin (about 10 cm. average thickness). The large "kicks" are due to α -particles. *c*. The same arrangement as in *b*, but an aluminium foil of 1.5 cm. stopping power covering the lithium target. The large kicks have practically disappeared.

Fig. 2. Ionization chamber containing a boron target (about 25 cm.²). Source (3 millicuries radon-beryllium) and chamber surrounded by paraffin.

neutrons, and also because argon is not disintegrated by slow neutrons. The chamber used for the gases was a parallel plate ionization chamber of 4.5 cm. depth and about 250 c.c. volume.

The chamber containing the element under investigation was exposed to the bombardment of neutrons from a radon-beryllium source, a block of lead being interposed between source and chamber to reduce the γ -ray background. A small number of ionization "kicks" was always observed, due mainly to recoil particles and sometimes partly to disintegrations by fast neutrons. The source and chamber were then surrounded by paraffin wax thus exposing the target (or gas) to the bombardment of slow neutrons. In the cases of lithium and boron a very large increase in the number of kicks, by a factor of the order of 100, was observed, indicating that a nuclear transformation was taking place.

3. *Lithium.* Both lithium metal and powdered lithium fluoride were used as targets. The oscillograph kicks appeared to be of two kinds, one due to doubly charged particles and one due to singly charged particles (see Plate VI, fig. 1a and b). Estimates of the ranges of the particles were made by repeating the observations when the lithium target was covered with aluminium foils of increasing thicknesses. We found that the range of the doubly charged particles corresponds to less than 1.5 cm. in air (see Fig. 1c) and that the range of the singly charged particles corresponds to about 5.5 cm. It does not seem possible to ascribe these particles to a reaction in which the main isotope of lithium (Li^7) is concerned, and the only transformation compatible with the measurements is



Using the revised atomic masses*

$$\text{Li}^6 = 6.0162, \quad \text{He}^4 = 4.0034, \quad \text{H}^3 = 3.0161 \quad \text{and} \quad n^1 = 1.0084,$$

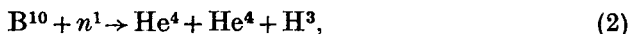
the energy release to be expected in reaction (1) is 0.0051 mass units or 4.7×10^6 e.v. Since the momentum of a slow neutron can be neglected, the He^4 and H^3 nuclei will be emitted in opposite directions with energies of 2.0 and 2.7×10^6 e.v. respectively; corresponding to ranges of 1.1 cm. and 6.3 cm. in air. This is in satisfactory agreement with the measurements given above and with the measurement of the sum of the ranges of the particles, viz. 6.9 cm. deduced by Taylor and Goldhaber† from tracks of this reaction observed in a photographic emulsion.

4. *Boron.* Boron was investigated using a target of powdered boron and also boron fluoride and boron chloride as gases. From the oscillograph deflections it appeared that the majority of particles emitted under the action of slow neutrons were doubly charged (see Plate fig. 2).

* Oliphant, Kempton and Rutherford, *Proc. Roy. Soc. A*, 150 (1935), 241. Bethe, *Phys. Rev.* 47 (1935), 634.

† Taylor and Goldhaber, *Nature*, 135 (1935), 341.

From observations when the target was covered with aluminium foils of different thicknesses it was estimated that the majority of the particles have ranges of less than 5 mm. in air but that a very small fraction of the particles had a greater range. This led us to suggest that the particles arose from the reaction



which also seemed to be the only reaction compatible with the values of the nuclear masses accepted at that time*. Amaldi and others† found that the maximum range of the particles was about 7 to 8 mm. of air and proposed the reaction

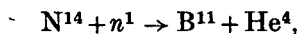


By observing the tracks of the particles from the boron reaction in a photographic emulsion Taylor and Goldhaber‡ showed that only two particles are emitted under the action of slow neutrons and that their combined range is 1.1 cm. This decides in favour of reaction (3). B. Kurchatow, I. Kurchatow and Latyshew§ have obtained expansion chamber photographs of the process and give ranges of 9.3 mm. for the α -particle and 3 mm. for the lithium nucleus. The total energy release in the reaction is thus 2.7×10^6 e.v. giving a mass for B^{10} of 10.0149, taking the revised values

$$n^1 = 1.0084, \quad \text{He}^4 = 4.0034, \quad \text{Li}^7 = 7.0170.$$

It may be noted that reaction (2) has been observed by Taylor|| to occur with fast neutrons. According to the revised masses the energy release in reaction (2) is nearly zero, and therefore if it happens with slow neutrons the disintegration particles would be difficult to observe.

5. *Nitrogen*. Nitrogen was examined with an ionization chamber filled with pure nitrogen. The number of kicks observed when the chamber and neutron source were surrounded by paraffin was two to four times as great, depending on the geometry, as without paraffin. From the sizes of the deflections we estimate that the energy released in the reaction is about 0.5×10^6 e.v. The disintegration process is probably



which, on the revised mass scale, should give an energy release of 1.4×10^6 e.v. with a probable error of about 1×10^6 e.v.

No marked disintegration effects could be observed in lithium, boron, and nitrogen, when any one of the four photo-neutron-sources RaTh-D, Rn-D, RdTh-Be, Rn-Be¶ was used *without* surrounding by paraffin.

* It seems that no reaction of a neutron with B^{11} can be exothermic.

† Amaldi and others, *loc. cit.*

‡ Taylor and Goldhaber, *loc. cit.*

§ B. Kurchatow, I. Kurchatow and Latyshew, *C.R.* 200 (1935), 1199.

|| Taylor, *Proc. Phys. Soc. London*, 47 (1935), 873

¶ Cf. Chadwick and Goldhaber, *Proc. Roy. Soc. A*, vol. 151 (1935), 479

6. We have also investigated a number of other elements for disintegration by slow neutrons, taking as a criterion the difference between the effects found with and without paraffin surrounding chamber and source. No appreciable increase was found for any of the following elements: *hydrogen* and *deuterium*, *helium*, beryllium*, carbon, *oxygen*, fluorine, *neon*, sodium, magnesium, aluminium, chlorine, *argon*, calcium, nickel, copper, zinc, indium, uranium (covered by aluminium foil of 3 cm. stopping power). Elements in italics were investigated as gas, the others as targets.

Indium was interesting because this element has only two isotopes but yet gives three radioactive bodies when bombarded by neutrons†.

Disintegration of uranium by slow neutrons with emission of α -particles could only be a probable process if α -particles of very high energy were emitted. They would then penetrate the aluminium foil of 3 cm. stopping power which was used to absorb the primary α -particles emitted by uranium.

7. *Discussion.* It was pointed out in the introduction that nuclear transformations produced by slow neutrons should occur only in special cases, generally speaking only with nuclei of very small mass defect and of low atomic number. This expectation is borne out by the experiments in which certain evidence for disintegration has been found only in three cases, viz. lithium, boron and nitrogen.

It is well known that lithium and boron strongly absorb "slow" neutrons; a beam of slow neutrons is reduced to half its intensity by a thickness of 0.23 gm./cm.² of lithium† or 0.015 gm./cm.² of boron‡. It seems that this strong absorption is mainly due to the disintegration process in which the isotopes Li⁶ and B¹⁰ only are concerned. The cross-sections for absorption of slow neutrons found for the elements must therefore be increased to take into account the proportions of the effective isotopes. (Li⁶ : Li⁷ = 1 : 11; B¹⁰ : B¹¹ = 1 : 4.) We thus obtain for the disintegration cross-section

of Li^6 about 4×10^{-22} sq. cm.

and of B¹⁰about 4×10^{-21} sq. cm.

The chief importance of the disintegration phenomena described in this paper lies in the fact that they afford a convenient and sensitive means of detecting the presence of slow neutrons. The natural effect of an ionization chamber is low, of the order of 1 kick per sq. cm. per hour, so that in experiments where observations can be made over some period of time the lithium or boron coated ionization

* The doubtful effect previously reported by us for this element was so small that we cannot be certain that it is not due to an impurity of lithium or boron.

† Szilard and Chalmers, *Nature*, 135 (1935), 493.

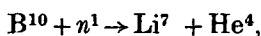
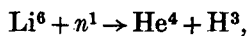
† Measured with lithium as neutron indicator by Dunning, Pegram, Fink and Mitchell, *Phys. Rev.* 48 (1935), 265.

§ Measured with boron as neutron indicator by Bjerge and Westcott, *Proc. Roy. Soc. A*, 150 (1935), 709.

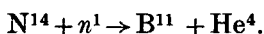
chamber is a very sensitive detector for slow neutrons. In the case of boron a gaseous compound, BF_3 or BCl_3 , can be used to fill the ionization chamber, and with appropriate gas pressure and length of the chamber a large fraction of the slow neutrons passing through the chamber will be absorbed and thus detected.

SUMMARY

All the light elements up to aluminium and some heavier ones have been examined for disintegration by slow neutrons. Large effects have been found in lithium and boron and a small effect in nitrogen, the reactions being



and probably



The charged particles emitted in the disintegration of lithium and boron afford a convenient and sensitive indicator for slow neutrons.

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